Ground level muons coincident with the 20 January 2005 solar flare

C. D'Andrea and J. Poirier

Department of Physics, University of Notre Dame, Notre Dame, Indiana, USA

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[1] An array of proportional wire chamber stations, Project GRAND, detects secondary muons produced by hadronic primaries. The muon counting rate at ground level increases above the average background intensity with a statistical significance of 10σ. This ground level event (GLE), caused by solar energetic particles, is detected in close time association with an X7.1 X-Ray flare on 20 January 2005. The statistical significance of this event rises to 18σ when an angular window of the sky near zenith is studied. These data are compared with data from neutron monitors.

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1. Introduction

[2] On 20 January 2005 NOAA reported an X7.1 (7.1×10^{-4} W/m^2 of X-Ray flux at the earth) X-Ray flare from the sun which began at 6:36 UT and peaked at 7:01 UT. The LASCO coronograph reported an associated CME from the WNW-NW limb at 6:54 UT. The protons recorded aboard the Earth-orbiting GOES satellite peaked at 7:10 UT for protons above 100 MeV (8:10 UT for protons >10 MeV) (NOAA Space Environment Center, http://www.sec.noaa.gov).

[3] The ground level muon counting rate of GRAND is examined for a sudden increase on 20 January 2005. There is a 10σ signal in the six minute interval from 6:51–6:57 UT. At this time GRAND was 160° away from the sun in azimuth. Neutron monitor detectors also see an increase in counting rate at approximately the same time. The mean primary energy for our excess depends on the signal's spectrum of energy but, in any case, is higher than the mean energies detected by neutron monitor detectors. Other ground level observations of energetic events from the sun have been detected [see, e.g., *Bieber et al.*, 2002; *Navia et al.*, 2005; *Poirier and D'Andrea*, 2002; *Swinson and Shea*, 1990].

2. Project GRAND

[4] Project GRAND (42°N 86°W, elevation 220 m a.s.l.) is an array of 64 proportional wire chamber stations arranged in an 8 × 8 grid over a 100 m × 100 m field. Each station contains four orthogonal pairs of wire chamber planes. Each plane has an active area of 1.29 m^2 and contains 80 wire cells. Pairs of planes are placed vertically above one another, separated by 197 mm. A 51 mm steel plate located above the bottom pair of planes allows muons to be differentiated from electrons (which stop, shower, or scatter in the steel 96% of the time); where muons are stopped or deflected by the steel only 4% of the time. The two orthogonal sets of chambers allow measurement of the angle of incident muons in the east-up projected plane and the north-up projected plane. The projected angles for each track are determined geometrically from the difference between the location of the wires hit on the top and bottom planes for each direction [*Poirier et al.*, 2003].

3. Analysis

[5] The muon counting rate for all stations was examined in three-minute bins from 5:00 UT to 10:00 UT on 20 January 2005. The ratio of $(rms\ deviation)/\sqrt{(number\ of\ particles)}$ was calculated for each station. Any station with a ratio above 1.10 was excluded from this analysis to ensure any signal detected is not the result of non-physical fluctuations within a station. This left 28 stations for consideration. Excluding the time from 6:48–7:09 UT, the systematic time dependencies of the background were fit from 5:00–10:00 UT with a quadratic curve. The curve is constant to within ±1% of the mean background counting rate (1.86×10^5 counts per three-minute bin). Figure 1 shows GRAND's data (circles, top points, left scale) as a percentage deviation from the fitted background curve. Error bars are statistical fluctuation based on the rms deviations from the background curve of 544 counts (which is 26% larger than the $\sqrt{N}$ estimator for the mean background counting rate). All subsequent error bars shown are also based on a calculation of rms deviation from background. We see a 9.9σ increase in muon counting rate (7759 ± 785 counts) above background in the two bins from 6:51 to 6:57 UT.

[6] These data are compared with data from the Newark and Oulu neutron monitors (Oulu Neutron Monitor Web site, http://spaceweb.oulu.fi/projects/crs; J. Bieber and R. Pyle, private communication, 2005; University of Delaware Bartol Research Institute Neutron Monitor Program, http://www.bartol.udel.edu/~neutronm). Figure 1 shows Newark's data (squares, bottom points, right scale) as a percentage of their background counting rate in comparison with GRAND (circles, left scale). Our signal peaks at the same time as Newark's while Oulu's signal (not shown) peaks nine minutes later. The later onset of Oulu's signal could be due to its sensitivity to lower proton energies or possibly its viewing direction. The counting rates for Newark and Oulu fall to half-maximum at 28 and 32 minutes after their peaks, respectively. GRAND's signal, on the other hand, is primarily contained within a six minute interval. This can be explained by a rigidity spectrum variance during this GLE with the spectrum becoming softer after the first six minutes following the onset.

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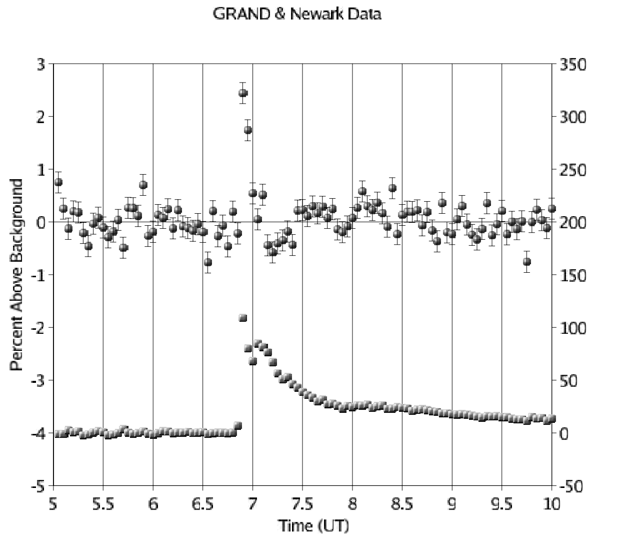

Figure 1. Data from Project GRAND (circles, left scale) and Newark neutron monitor (squares, right scale) in three-minute bins as a percentage deviation from background. Error bars from GRAND are rms fluctuations from the time dependent background; points are plotted at the end of their time interval. See color version of this figure in the HTML.

[7] The energy thresholds for Newark and Oulu neutron monitor stations are influenced by their vertical geomagnetic cutoff rigidities at 2.1 and 0.8 GV respectively (University of New Hampshire Space Physics Web site, http://ulysses.sr.unh.edu/NeutronMonitor/neutron_mon.html). GRAND, on the other hand, is more influenced by the energy spectrum of the primaries than its geomagnetic cutoff. For galactic cosmic ray energy spectra, our median primary energy is 52 GeV (K. Munakata, private communication, 2004), but this would be lower for the softer spectrum expected for particles emitted from the sun during a flare. In order to detect secondary muons at ground level, hadronic mesons must first be produced which then decay to charged muons. The muons need to be created with sufficient energy to reach the ground after undergoing ionization energy loss in the atmosphere. The processes which are required for ground level detection of neutrons for neutron monitors are less stringent because the neutrons 1) require less energy to be produced at the first primary interaction and 2) do not suffer ionization energy loss through the atmosphere. Therefore the primary energies to which GRAND is sensitive during a ground level event are higher than those of neutron monitor stations.

[8] The angular information for the muons were then examined for the same time period as above. The mean projected angle of incidence for the muons was calculated for each bin. The mean angle for the east-up plane was 0.09° from the west. During the same two time bins (6:51–6:57 UT) as the increase in counting rate, the mean incident angle of the muons switched to 0.07°E, a shift of 0.16° ± 0.04°. There is no significant shift (0.3σ) in the mean angle in the north-up projected plane. In order to investigate the possibility of an excess of muons from particular angles, the sky was divided into a 15 × 15 grid of angular regions with approximately equal counting rates. The excess appeared to be roughly limited to a central box of 6 × 7 bins. This is an area from 13°S to 10°N and 10°W to 18°E where the angles are measured from vertical in the appropriate projected plane. This angular area of the sky was isolated and analyzed by again fitting the systematic time dependencies of the background to a quadratic curve from 5:00–10:00 UT with the same times excluded as in the all-sky analysis. The curve is constant to within ±1.6% of the mean background of 1.24×10^4 counts per one-minute bin. The results are shown in Figure 2 in one-minute intervals. There is an increase in counting rate above background from 6:51–6:57 UT for these centrally located angles with an rms deviation of 121 counts. The highest one-minute bin has an increase of 13% above background. Using the same six minutes of signal time (6:51–6:57 UT), there is an excess of 5458 ± 308 counts (17.7σ statistical significance). This increased significance for muons near vertical angles could be due to the arrival direction of the solar protons, their softer energy spectrum relative to the ambient cosmic rays, or both. At the time of this event, GRAND was 160° away from the sun in azimuth. Therefore the cause of the signal cannot be from gamma rays or neutrons traveling on a direct path from the sun. Anti-sunward particles have been detected by ground-based neutron monitors, for example, during the flare of October 28, 2003 [*Bieber et al.*, 2005].

4. Conclusions

[9] A 9.9σ excess is seen in the single muon counting rate from 6:51–6:57 UT. The peak occurs at the same time as the Newark neutron monitor signal and precedes the peak for the Oulu neutron monitor by nine minutes. At the same time as our increase in counting rate is a shift in the average

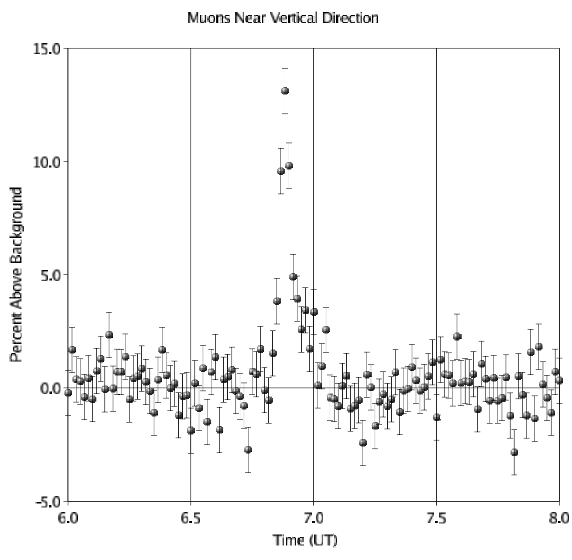

Figure 2. Data showing GRAND's counting rate in one-minute bins for an angular area of the sky from 13°S to 10°N and 10°W to 18°E. This is an expanded scale, plotting only data from 6:00–8:00 UT. Error bars represent rms fluctuations from the background curve; points are plotted at the end of their time interval. See color version of this figure in the HTML.

angle of incoming muons. When angles close to the center portion of the sky (near zenith) are selected, the statistical significance of the increased counting rate rises to 17.7σ.

[10] Added information about the primary energy spectrum, time envelope, and pitch angles of particles emitted by the sun during the event can be obtained by combining GRAND's data with data from neutron monitor stations with their different energy sensitivities. Further information can be gained by combining this analysis with data from other muon detectors at different geographical locations. We will make this data available to anyone interested in making a combined fit with other muon and neutron detectors for this ground level event.

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C. D'Andrea and J. Poirier, Department of Physics, University of Notre Dame, 225 Nieuwland Science Hall, Notre Dame, IN 46556-5670, USA. (cdandrea@nd.edu)